Anisotropic Behavior of Granular Materials: Impact on Flexible Pavement Design

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Abstract. This study investigated the effect of anisotropic behavior of granular material in flexible pavement and quantify the effect on the overall design of the flexible pavement. The major scope of this study included design of flexible pavement based on conventional design using layered-elastic theory and anisotropic behavior of granular materials. These properties were considered through resilient modulus of granular and modeled through finite element modeling. 3D elemental model obtained from ABAQUS utilized similar material properties and loading conditions to simulate pavement responses. Pavement performance was predicted based on IRC 37: 2018 pavement design guidelines. It was found that the anisotropic behavior of granular materials overestimated the material properties which can potentially lead to premature failure.

Keywords: Pavement Design, Anisotropic Behavior, Finite Element Modeling, Design Life.

1 Introduction

Flexible pavement consists of bituminous mixtures placed on compacted aggregates over soil subgrades. The load-transfer mechanism of flexible pavement employs distribution of load through different layers where the load magnitude diminishes as the load is transmitted downwards. Using this framework, the mechanic characteristics of pavements such as: stress and strain at different locations are estimated. In general, these mechanics characteristics are used as inputs in the mechanistic-empirical design of flexible pavement.

Globally, flexible pavement is designed based on mechanistic-empirical pavement de-sign methodology. In this system, strain is calculated based on layered-elastic theory and then the strains at different locations are considered indicators of pavement performances. For instance, in India, flexible pavement design is conducted based on majorly two performance criteria. These performance criteria include (a) rutting and (b) fatigue cracking. Even though these two criteria depend on several other design variables such as traffic level, reliability, percentage volume of air voids, and percentage volume of bitumen in the mix design, the mechanics characteristics of materials are broadly covered through strains. For rutting, the compressive strain at the top of the soil subgrade is considered whereas the tensile strain at the bottom of asphalt layer is used for the estimation of fatigue performance.

Fundamentally, the strains estimated through layered-elastic theory is largely dependent upon the resilient modulus of various layers of pavement. One of the major assumptions considered in the estimation of strain employs isotropic behavior of materials. This assumption helps an easy estimation of materials' properties using layered-elastic analysis. However, since the granular layer is made up of various types of materials, anisotropic behavior remains prevalent instead of isotropic.

Research studies [1-3] have shown strong evidence of nonlinear cross-anisotropic elastic behavior of granular materials. In literature, such behavior was modeled using nonlinear cross-anisotropic modeling at different materials types, gradation, moisture content, and stress levels. In another direction, several studies [4-5] were conducted to incorporate the realistic material properties of the pavement layer and the moving traffic load in the analysis of the flexible pavement using the finite element analysis. With regard to the loading system, linear, nonlinear, static, and cyclic loading analysis were also considered to simulate realistic traffic loading. It was found that if pavement designs are carried out assuming static loading and linear pavement materials, the deflection at the top of the subgrade becomes higher than the expected values when pavement section with non-linear [7-9]. Several other research studies [10-12] utilized triaxial tests to assess the aggregate physical properties and their effects on the cross-anisotropic behavior of unbound granular materials. These physical properties include particle shape, form, angularity, texture, and gradation. It was highlighted that the advantage of the use of cross-anisotropy for the analysis of unbound granular bases is the drastic reduction of bottom tensile stresses predicted by linear elastic analysis based on the assumptions of isotropy [13-16].

Although a wealth of literature can be found that investigated the impact of anisotropic behavior of granular materials, very limited studies can be found that explored the impact of anisotropic behavior of granular materials on design and/or performance. With this background, this study investigated the effect of anisotropic behavior of granular materials and quantify the effect on the overall design of the flexible pavement. The scope of the study included:

- Conduct a comprehensive literature review pertinent to the material characterization and design consideration of granular materials;
- Analyze the effect of linear and nonlinear stress-strain variation in Granular Sub-base (GSB)layer;
- Simulate anisotropy behavior of the material through finite element model;
- Assess strains due to the anisotropic behavior using ABAQUS$^{®}$ model; and
- Quantify the change in estimated design lives based on strains characteristics

2 Theoretical Background and Relevant Literature

Nonlinear behavior is commonly characterized by stress-dependent resilient modulus. In general, resilient modulus is assigned to finite element-based mechanistic pavement analysis methods to predict the pavement responses such as stress, strain, and deformation [17-21]. Further, analysis of a typical flexible pavement considering the cross-anisotropy of the granular base layer shows that the values of critical mechanistic parameters (ε_v and ε_t) are higher than the isotropic material properties. With the variation of the degree of cross-anisotropy, the value of ε_v and ε_t increased, causing a reduction in rutting and fatigue lives [22-23].

Many research studies [22-24] found that the consideration of the anisotropy behavior of granular materials shows a more accurate and more realistic estimation of the critical mechanistic parameters instead of consideration of the isotropic behavior of granular materials. In the design guidelines of the flexible pavement, IRC 37: 2018 [25] the isotopic behavior of granular materials is considered for the analyses and design purpose which makes a less accurate design [24].

3 Finite Element Modeling

A finite element-based software ABAQUS® was used for modeling the pavement section. ABAQUS® model was prepared for the two different cases. In the first case, the model was prepared for the simple isotropy case. In that case, the whole granular layer shows the isotropic behavior. The critical strain values obtained from the analysis of this model were used in the calibration of the new design parameters for the next pavement model that considered the anisotropy in the granular layers. In the second case, the pavement model is prepared for a new calibrated design parameter that shows the anisotropic behavior of the granular layer. For that purpose, the whole granular layer is divided into the number of layers of equal thickness. For both models, the impact of mesh size was determined and a global mesh size of 0.8 provided the optimum accuracy. Furthermore, the boundary condition of the pavement layers was fixed at four sides while the base extended to infinite in vertical plane. At first, the pavement section was designed with the help of IRC 37:2018 [25] and critical strains were obtained. The input parameters used in the design are summarized in Table 1.

Table 1. Critical Strain Values Obtained from IITPAVE and ABAQUS

IITPAVE Model: Sectional Area: (3000 x 3000) mm^2						IITPAVE	
CBR	MSA	Layer	Modulus (MPa)	Poisson ratio	Thickness (mm)	Vertical Strain	Tensile Strain
8%	30	Binder	3000	0.35	150	3.51x10^{-04}	1.88x10^{-04}
		Granular	199	0.35	410		

		Soil	67	0.35	-		
ABAQUS Model: Sectional Area: (3000 x 3000) mm^2						ABAQUS	
8%	30	Binder	3000	0.35	150	1.94 x10^{-04}	9.12x10^{-05}

Next, a 3D pavement model was prepared in ABAQUS® as shown in Fig. 1 (a). The dimensions and other properties of pavement section were the same for the ABAQUS model. Then, standard wheel load was applied and critical strain values were estimated as illustrated in Fig. 1 (b).

To improve the accuracy of the model, a strain calibration was conducted with respect to the strains obtained from elastic layer analysis. With this, ABAQUS® model was made possible to capture only the impact of non-linearity and cross-anisotropy since all other design parameters of models remained the same. Considering the calibrated design parameters, a 3D pavement model was prepared in the ABAQUS®. In this model, the thickness of the granular layer was divided into the number of layers of equal thickness in vertical direction as shown in Figure 2 (a). Similar to the previous model, standard wheel load was applied in the model and critical strains were determined as shown in Figure 2 (b).

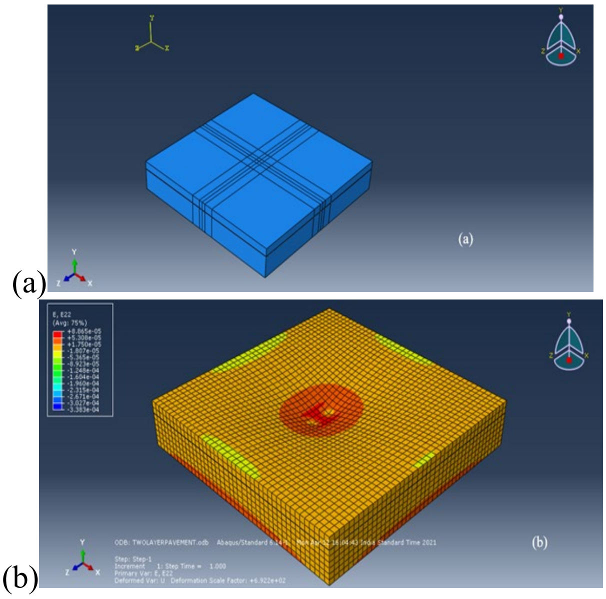

Fig. 1. Finite Element Modeling of pavement: (a) model element, and (b) deformed model characteristics

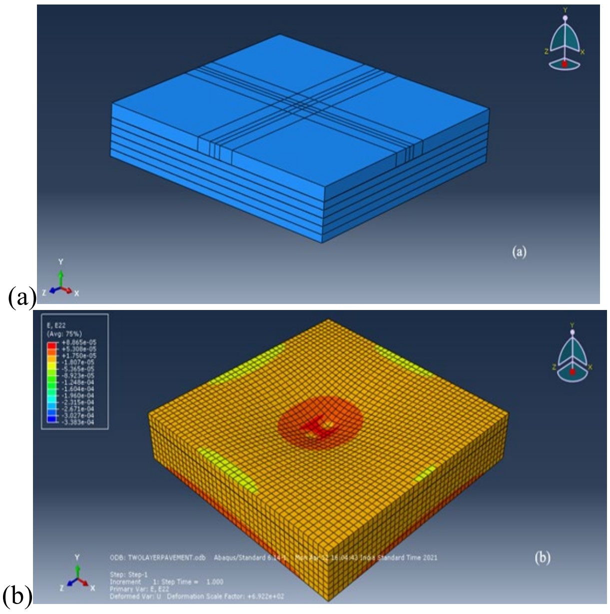

Fig. 2. Finite Element Modeling accounting for non-linearity: (a) model elements in which granular materials were divided, and (b) deformed model characteristics

4 Results and Analyses

4.1 Estimation of Critical Strain Values

To compare the linear-elastic behavior and anisotropic behavior, it is deemed important to idealize a pavement section. With this idealized section, isotropic and anisotropic properties were assigned in the ABAQUS® model and corresponding strains were estimated. For this purpose, a pavement section was designed as per the IRC 37:2018 [25] with 30 MSA design traffic volume and 8% CBR of sub-grade soil. Next, critical strains were estimated using the design equations provided in IRC 37:2018 [25] with 90% reliability. After that, a set of trial thick-nesses were calculated using modulus values summarized in Table 1. Using IIT-Pave software, tensile strain at the bottom of asphalt layer (ε_t) and compressive strain at the top of the subgrade (ε_z) were estimated; these are incurred strains of the pavement section with trial thickness. When the incurred strains obtained from the trial section were lower than the critical strains obtained from IRC 37:2018 [25] with 90% reliability, it was considered design thickness. For all the finite element modeling, these thicknesses of pavement section were idealized; and different material properties, such as isotropic and anisotropic section were assigned in modeling to account for materials' variability.

Next, a pavement section was modeled with the help of the ABAQUS®. In the process, a simple model of two-layered pavement sections was created and a standard wheel load was applied to the model to simulate the critical strains of pavement. Here, critical strains refer to tensile strain at the bottom of the asphalt layer and compressive strain at the top of subgrade layer. Then, to improve the accuracy of the ABAQUS model, it was calibrated based on the critical strains obtained from IITPAVE software.

4.2 Critical strain and traffic level Estimation

The calibrated ABAQUS® pavement model was used to simulate non-linear elastic behavior. It is important to note that the modulus of materials for non-homogeneity does not consider a single value of modulus and thereby necessitating different variations in moduli across the vertical direction. Even though no defined variation may be observed for granular material, modulus was varied in a defined format to illustrate the magnitude of change and its associated impact on pavement performance. These variations were carefully selected in order to capture gradual and non-consistent changes in the properties of granular materials.

The resilient modulus of the granular sub-base layer was increased from 100 MPa at the top and 200 MPa at the bottom in different variations. Since a modulus value of 200 MPa was selected for layered-elastic theory for granular layer (Table 1), a similar magnitude of modulus was considered here to make it comparable. With these initial and final limits, the modulus was varied in four variations, namely: (i) linear variation (Fig. 3(a)), (ii) quadratic variation (Figure 3(b)), (iii) exponential variation (Figure 3(c)), and (iv) Logarithmic variation (Figure 3(d)).

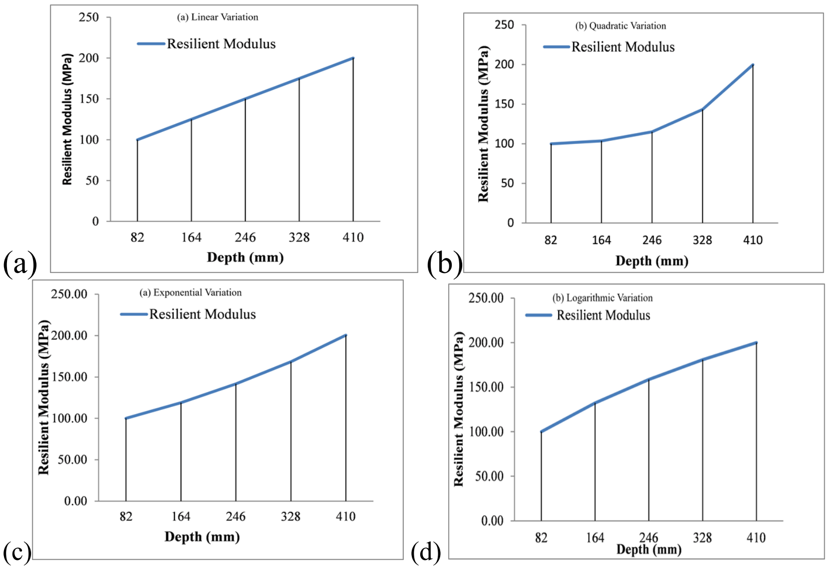

Fig. 3. Variation in Modulus: (a) Linear, (b) Quadratic, (c) Exponential, and (d) Logarithmic

Four separate models were prepared for each variation and critical strains were calculated. Next, these critical strains obtained from each model were used to predict the rutting and fatigue life as per IRC 37:2018 [25] design equation with 90% reliability. It is important to recall that the dimensions and thicknesses of all these models were kept the same as summarized in Table 1. Critical strains obtained from all four variations and associated rutting and fatigue lives are summarized in Table 2.

Table 2. Critical strains and estimated lives

Variation	Tensile Strain	Vertical Strain	Traffic Level (MSA)	
			Fatigue	Rutting
Linear	$1.97\text{x}10^{-04}$	2.96x^{-04}	33.80	140.39
Quadratic	$2.05\text{x}10^{-04}$	$3.72\text{x}10^{-04}$	28.95	49.81
Exponential	$1.99\text{x}10^{-04}$	$3.63\text{x}10^{-04}$	32.49	55.66
Logarithmic	$1.95\text{x}10^{-04}$	$3.58\text{x}10^{-04}$	35.16	59.28

When the model findings are compared, deviation in performance and strain can be quantified. The strain values summarized in Table 2 can be benchmarked with the strain obtained from the layered-elastic analysis. Furthermore, the rutting and fatigue performance can be compared with 30 MSA design traffic since the pavement section was idealized for 30 MSA design traffic. The major findings can be summarized as follows:

- *Linear Variation*: tensile strain for linear variation was more than the design critical tensile strain. And vertical compressive strain was less than the design critical vertical strain. The corresponding traffic level in MSA was more than the design traffic (30 MSA). Thus, for the linear variation, the strength of the granular materials was underestimated.
- *Quadratic Variation*: Strains for quadratic variation was found higher than the design critical strain. In addition, the estimated rutting and fatigue life were found to be lesser than 30 MSA. Hence, for the quadratic variation, the strength of the granular materials was overestimated.
- *Exponential Variation:* Strains for exponential variation were more than the design critical strain and the corresponding traffic level in MSA was more than the design traffic. Thus, for the quadratic variation, the strength of the granular materials was underestimated.
- *Logarithmic*: Strains for logarithmic variation were more than the design critical strain and the corresponding traffic level in MSA was more than the design traffic. Hence, for the quadratic variation, the strength of the granular materials was underestimated.

As observed, nonlinearity in the granular layer had a significant effect on the rutting and fatigue performance of the flexible pavement. A comparison of the estimated traffic level with the design traffic level showed the overestimation or underestimation of the strength of the granular materials when anisotropy was considered. Expect the linear variation in modulus, all other variations produced lower design traffic which was an indication of overestimation of material properties. In practice, though the variation in granular materials does not follow any particular pattern, the findings showed that any variation in modulus other than linear distribution potentially reduces the performance of the pavement. This may lead to a serious concern since any variation of modulus triggers the pavement to fail in prematurely. This is especially true when stress-dependent non-linearity is exemplified by granular materials.

5 Research Significance

A significant contribution of this study was to analyze the effect of the anisotropic behavior of granular material in the design of flexible pavement. Different types of non-linear variation in resilient modulus at various depths of the granular layer were analyzed in this study. This study was the first of its kind since it considered the anisotropic behavior in the granular layer and its effect on the design traffic level. It is noteworthy that the findings of the study set a strong platform towards advancing the state-of-the-art and knowledge pertaining to the impact of non-linear behavior of materials on pavement performance.

- *Anisotropic behavior of granular materials*: Anisotropic properties are considered instead of isotopic granular materials properties using finite element modeling. The model was calibrated and then used in tandem with the layered-elastic theory to capture the anisotropic behavior of granular materials. The methodology was simple but powerful enough to differentiate the changes in material properties in terms of strains and performance.
- *Non-linearity in the granular layer:* The granular layer was divided into different layers of equal thickness. Resilient modulus values are increased from bottom to top with different types of nonlinear variation. For each variation, the strains at critical locations were simulated with the help of ABAQUS® model, and then used to calculate the design traffic based on IRC 37:2018 [25].
- *Estimation of traffic level*: For each nonlinear variation, separate design traffic was found and that traffic level was compared with the design traffic obtained from layered-elastic theory. After comparisons, an overestimation of material properties was observed if granular material does not remain isotropic. When the variation in modulus was linear, the analysis of layer-elastic theory still remains valid in terms of performance. However, non-linear variation caused an overestimation of material properties which can eventually lead to premature failure of the pavement.

6 Conclusions

The objective of this study was to investigate the impact of the anisotropic behavior of the granular material and quantify the effect on the overall design of flexible pavements. An idealized pavement section was used for understanding the impact of anisotropy through finite element modeling. The pavement section designed with layered-elastic theory was compared with the pavement section of anisotropic behavior. Based on the strains, the performance of pavement was estimated using mechanistic-empirical design.

It was observed that any variation in modulus, expect linear increment overestimate the material properties. If such overestimation is considered in pavement design, it may potentially lead to premature failure of the pavement. Certainly, this finding was extracted based on the assumption that the performance equation of design guidelines remains valid for the strain derived from anisotropic material properties. Even though the assumption of performance prediction does not provide an accurate measure of the anisotropic behavior of materials, it broadly addressed the impact of anisotropic materials' properties. A similar methodology with finite element modeling can be implemented in conjunction with the various other performance prediction models. More sophisticated materials properties can be used in the future to account for stress-dependent non-linear properties of granular materials using advanced finite element modeling.

References

[1] R. S. Harichandran, M.-S. Yeh, and G. Y. Baladi, “MICH-PAVE: A nonlinear finite element program for analysis of flexible pavements,” *Transp. Res. Rec.*, no. 1286, 1990.

[2] R. G. Hicks and C. L. Monismith, “Factors influencing the resilient response of granular materials,” *Highw. Res. Rec.*, vol. 345, pp. 15–31, 1971.

[3] I. Al-Qadi, H. Wang, and E. Tutumluer, “Dynamic analysis of thin asphalt pavements by using cross-anisotropic stress-dependent properties for granular layer,” *Transp. Res. Rec.*, no. 2154, pp. 156–163, 2010, doi: 10.3141/2154-16.

[4] Q. Liu and A. Shalaby, “Simulation of pavement response to tire pressure and shape of contact area,” *Can. J. Civ. Eng.*, vol. 40, no. 3, pp. 236–242, 2013.

[5] A. Nataatmadja, “On the response of granular unbound pavement materials under repeated loading,” 1994.

[6] Y. H. Huang, “Pavement analysis and design,” 2004.

[7] L. Wang, L. R. Hoyos, J. Wang, G. Voyiadjis, and C. Abadie, “Anisotropic properties of asphalt concrete: characterization and implications for pavement design and analysis,” *J. Mater. Civ. Eng.*, vol. 17, no. 5, pp. 535–543, 2005.

[8] IALA-AISM, “Guidelines for the design of footbridges,” *IALA Guidel.*, no. December, pp. 1–37, 2001, [Online]. Available: http://trid.trb.org/view.aspx?id=873476.

[9] J. H. Oh, R. L. Lytton, and E. G. Fernando, “Modeling of pavement response using nonlinear cross-anisotropy approach,” *J. Transp. Eng.*, vol. 132, no. 6, pp. 458–468, 2006, doi: 10.1061/(ASCE)0733-947X(2006)132:6(458).

[10] T. Pan, E. Tutumluer, and J. Anochie-Boateng, “Aggregate morphology affecting resilient behavior of unbound granular materials,” *Transp. Res. Rec.*, no. 1952, pp. 12–20, 2006, doi: 10.3141/1952-02.

[11] M. N. S. Hadi and B. C. Bodhinayake, “Non-linear finite element analysis of flexible pavements,” *Adv. Eng. Softw.*, vol. 34, no. 11–12, pp. 657–662, 2003, doi: 10.1016/S0965-9978(03)00109-1.

[12] S. Underwood, A. H. Heidari, M. Guddati, and Y. R. Kim, “Experimental investigation of anisotropy in asphalt concrete,” *Transp. Res. Rec.*, vol. 1929,

no. 1, pp. 238–247, 2005.

[13] J. Uzan, “Characterization of Granular Material.,” *Transp. Res. Rec.*, pp. 52–59, 1985, doi: 10.1016/0148-9062(86)91013-2.

[14] A. Nataatmadja and A. K. Parkin, *Characterization of granular materials for pavements*, vol. 26, no. 4. 1989.

[15] A. Adu-Osei, “Characterization of unbound granular layers in flexible pavements. Report No.ICAR/502-3,” p. 260, 2000, [Online]. Available: https://repositories.lib.utexas.edu/bitstream/handle/2152/35440/502-3.pdf?sequence=2&isAllowed=y.

[16] S. H. Kim, D. N. Little, E. Masad, and R. L. Lytton, “Estimation of level of anisotropy in unbound granular layers considering aggregate physical properties,” *Int. J. Pavement Eng.*, vol. 6, no. 4, pp. 217–227, 2005, doi: 10.1080/10298430500335244.

[17] M. Kim, E. Tutumluer, and J. Kwon, “Nonlinear Pavement Foundation Modeling for Three-Dimensional Finite-Element Analysis of Flexible Pavements,” *Int. J. Geomech.*, vol. 9, no. 5, pp. 195–208, 2009, doi: 10.1061/(asce)1532-3641(2009)9:5(195).

[18] C. Johnson, “This is an Accepted Manuscript of an article published by Taylor & Francis Group in,” vol. 53808, no. April, pp. 1–32, 2007.

[19] B. Ghadimi and H. Nikraz, “A comparison of implementation of linear and nonlinear constitutive models in numerical analysis of layered flexible pavement,” *Road Mater. Pavement Des.*, vol. 18, no. 3, pp. 550–572, 2017.

[20] Y. Cai, A. Sangghaleh, and E. Pan, “Effect of anisotropic base/interlayer on the mechanistic responses of layered pavements,” *Comput. Geotech.*, vol. 65, pp. 250–257, 2015, doi: 10.1016/j.compgeo.2014.12.014.

[21] U. Seyhan, E. Tutumluer, and H. Yesilyurt, “Anisotropic aggregate base inputs for mechanistic pavement analysis considering effects of moving wheel loads,” *J. Mater. Civ. Eng.*, vol. 17, no. 5, pp. 505–512, 2005.

[22] B. Beriha and U. C. Sahoo, “Analysis of flexible pavement with cross-anisotropic material properties,” *Int. J. Pavement Res. Technol.*, vol. 13, no. 4, pp. 411–416, 2020, doi: 10.1007/s42947-020-0284-9.

[23] Y. Ozawa and J. Maina, “Influence of Cross-Anisotropy Material Behavior on Back-Calculation Analysis of Multi-Layered Systems,” *Analysis*, no. July, pp. 27–34, 2008.

[24] W. J. V. der M. Steyn, J. W. Maina, and A. Repsold, “Comparison of isotropic and cross-anisotropic analysis of pavement structures,” 2013.

[25] IRC 37:2018, "Guidelines for the design of flexible Pavement", Fourth Revision, Indian Roads Congress, New Delhi, India.